



Short communication

Vibration test methods and their experimental research on the performance of the lead-acid battery[☆]Baoxiang He^{*}, Hua Wang, Xie He

School of Information Science and Engineering, Changzhou University, Changzhou 213164, China

HIGHLIGHTS

- Collects the real-time state parameters for calculation, analysis and judgment.
- Self-adapts to the ideal target values.
- Load compensation technology.
- A number of lead-acid battery voltage self-adaption and accomplished a variety of high-precise tests.

ARTICLE INFO

Article history:

Received 4 November 2013

Received in revised form

16 April 2014

Accepted 21 May 2014

Available online 12 June 2014

Keywords:

Lead-acid battery

Impact excitation

Free oscillation

Detection technology

Adaptive fuzzy

ABSTRACT

As we know, Lead-acid battery is difficult to balance many factors such as the accuracy and the on-line testing requirement. The detecting system, as stated in this article, is based on the vibration test procedure, dynamically following the electrochemical process of the Lead-acid Battery, and collects the real-time state parameters for calculation, analysis and judgment. It also quantizes precisely the degradation and chargeability of the battery and therefore self-adapts to the ideal target values. During the test, it has not charged and discharged large current to the lead-acid battery, it only plus a smaller and shorter time of impulse voltage signal on both ends of lead-acid battery, so the battery measured is damage free, and the system energy consumption is small; Using the load compensation technology, it has solved the influence of load on the test results. What's more, the load characteristics are improved at the same time, it realized the online detection. The vibration detection is based on the adaptive fuzzy inference model which has taken various factors into account, concerning the choices of input aspects which may influence the output value. It realized a number of Lead-acid Battery voltage self-adaption and accomplished a variety of high-precise tests.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

In 1859, Plante invented the lead-acid battery which has many advantages like rich material source, high power, stable performance, safety, technology and mature manufacturing technology, high electromotive force and good charge and discharge reversible electrochemical principle [1]. It also has a wide temperature range, clearly electrochemical principles, high rate renewable resources recovery and the power performance and practical application

efficiency are high but technique of production is easy to grasp and low in price [2]. At present, it has become one of the maturest technical batteries. Lead-acid batteries, however, is a complex electrochemical system, its performance status, such as capacity, failure mode and aging degree were affected by the lead-acid battery's pole plate corrosion, sulfation, electrolyte dry and hot out-of-control. Therefore, the fast accurate examination to lead-acid battery performance condition is very difficult [3]. Compared with the rapid development of the lead acid battery, the research and development of the performance test is lagging way behind, whether early method for measuring the voltage value or recent widely applied methods, the discharge method and the conductance measurement method are all have obvious deficiencies [4].

Voltage measurement method, due to the fact that under the lead-acid battery floating state, whether the performance is good or

[☆] Project supported by the National Nature Science Foundation of China (No. 51075045), Government-supported Scientific and Technological Project of Changzhou City, Jiangsu Province (No. CE20112026); Key laboratory of digital manufacturing technology projects Supported by Jiangsu Province, China (No. HGDML-0702).

^{*} Corresponding author. Tel.: +86 13951228872; fax: +86 (0)51986330558.
E-mail address: 15061972883@163.com (H. Wang).

bad, there are no obvious differences nor the reliable regularity to follow, thus this technology were soon be eliminated [5].

The check and discharge test, namely the lead-acid battery at a constant current or voltage of load discharge, checks and calculates the real capacity through the discharge parameters and the expert data [6]. The advantage of this method lies in the accurate and reliable test that can accurately judge whether battery is failure or not. Nowadays it is still the most effective and reliable way to test the state of battery performance [7]. To some extent, checking the discharge of the battery can also do maintenance to the battery [8]. But the downsides of this method are fairly obvious, which can be showed mainly in the following aspects: it requests the battery to work off the system and can't be monitored online. What's more, the operating time is too long and accompanied by high risk, besides, the tested battery must be out of work status, the energy stored in the battery are consumed in the form of heat energy during the offline measurement, then, at the same time the tedious process causes the waste of energy [9]. The conditions are complicated as to ensure the utility would not be affected by the test, so it generally requires a spare battery, otherwise it will increase the risks of system power failure. Battery internal chemical reaction is irreversible, frequent deep discharge will cause the lead sulfate precipitation, result in the plate sulphation and eventually make its capacity drop, shorten its life. The detection method discharge the energy to the entire group of work in series battery, therefore it can only measure the capacity for the whole and not measure the battery capacity for each session, while each of the monomer battery capacity is not the same. The standard to be calculated in the process of testing would become the minimum capacity, at the same time, higher capacity battery is not completely discharged which also can affect the accuracy of the test [10]. So the check the discharge test is only applicable to the regular maintenance of storage battery, it cannot meet the daily maintenance and online monitoring [11].

Conductivity measurement, refers to by monomer battery conductance or resistance within the size to measurement and calculation that determine the performance of the lead-acid battery. But a lot of experimental data show that only after the battery capacity decreased to 50% [12], its conductivity or the resistance value should have more obvious changes. So, degradation of high measure battery is suitable for using this method, while this method is not for degradation of low battery to provide accurate data for reference [13]. Therefore the method of testing conductance or calculated value can only provide valuable judgment basis in a certain range of battery performance, and it has no enough energy to accurately calculate all state performance of the lead-acid battery.

All in all, currently, the methods of testing lead-acid battery performance is in low accuracy, with high measurement requirement, narrow range and long measurement cycle; what's more, its risk is big, and lowers the quality of the battery, and can't be monitored online as well [14]. In order to ensure the normal work of the power system on traction, communications and many other areas, it needs to increase the lead-acid battery to a significant level on maintenance and inspection [15]. Therefore, at present, to explore a rapid, accurate, reliable and safe test method has become the enthusiasm on research topics.

2. Test method of vibration on lead-acid battery performance

2.1. Loop of the detection

Fig. 1 shows the lead-acid battery performance of the on-line detection in main loop. In the battery equivalent model, R_{01} , R_{02} were positive and negative electrode polarization resistance, for R_{03}

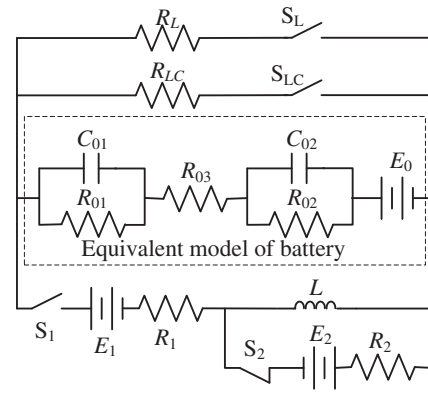


Fig. 1. The main loop of the lead-acid battery performance testing.

batteries is ohm resistor, C_{01} , C_{02} are polarization capacitance of the positive and negative electrodes, E_0 works for the positive and negative electrode voltage; E_1 , R_1 and E_2 , R_2 are two numerical control dc voltage source. L is a standard inductor. S_1 , S_2 and S_{LC} are electric control switch; R_{LC} is automatic compensation resistor. R_L is load and S_L is manual control switch.

During detection, the first thing is to get the lead-acid accumulator electrode voltage E_0 to match numerical control power supply E_1 ($E_1 = E_0$); Depending on the battery under test, adjust the calibration resistor of R_1 to ensure the high quality on damping oscillation; E_2 and R_2 must be guaranteed to obtain a suitable current on L as the impact test power source; And disconnect the S_2 and close S_1 . Then both ends of the battery will be plus a very small damping oscillation superimposed on the E_0 . The oscillating voltage can comprehensive characterize battery's characteristic parameters (such as ohm resistor R_{03}), then it can obtain and analyze the performance of the battery. Since the oscillating voltage attenuation is small enough to maintain a short time, so it does not affect load work and can realize on-line measurement.

To overcome the effects of load variation on the detection accuracy, across the load we paralleled with a program-controlled variable resistor R_{LC} , when the trigger switch is detected by the S_{LC} we can realize intelligent compensation. Fig. 2 shows the relationship between load current i_{RL} , compensation resistor current i_{RLC} and the output current i_R , under normal circumstances, when the load changes, the output current of the battery can be kept constantly by compensating i_R . Therefore, compensation resistor R_L eliminates the effect of changes in the load on the battery performance test accuracy, compensating output current i_R can be

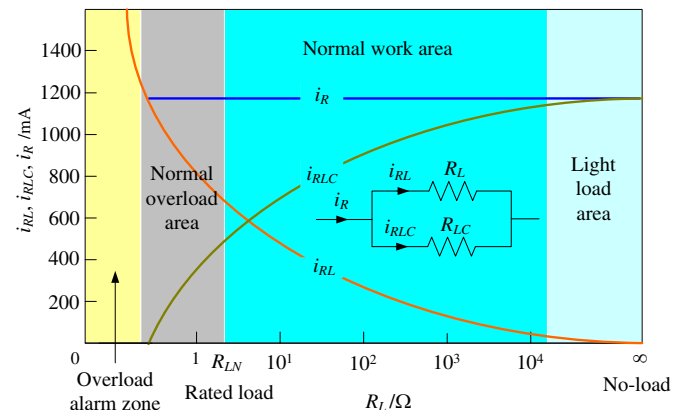


Fig. 2. Relationship between the load current and the compensation current.

arbitrarily set, and the more larger setting, the wider scope of compensation will be, but the compensation current i_{RLC} increased the burden on the battery, so i_R should not be set too large, the detection point should not too dense.

2.2. Test system

Lead-acid battery performance of vibration test method is based on high performance processing capabilities of DSP which is combined with the high speed data acquisition of CPLD to implement battery test online. Test system is shown in Fig. 3. The system is mainly composed of DSP master control module, the main loop of the high-speed data acquisition module, CPLD module and other components. Main circuit under DSP control catches an oscillation waveform, then via high speed acquisition of CPLD and temporarily storage in RAM. By the DSP with expert database system, calculation, comparison and analysis, it gets the measured performance of the battery, and displays it on the LCD screen.

The DSP we chosen is TMS320LF2407 made by TI company, specially designed for control applications, which has a good performance, and it has a 16-bit DPS chip. The controllable gain amplifier adopts differential structure in order to improve the common-mode interference suppression ability. We choose AD7938 which has 12 parallel high-speed, low power consumption ADC and can handle input frequencies signal up to 50 MHz we choose the XC95144XL to share the acquisition and preprocessing task of DSP signal. The arm we selected is IS61LV51216. It is the bit high speed asynchronous static RAM of $512\text{ K} \times 16$ which is used to store voltage sampling signal. The read/write control sequence is produced by CPLD.

Expert database system is built by the neural Network Adaptive Fuzzy Inference (the Adaptive Network-based Fuzzy Inference System, ANFIS). ANFIS not only adopts the advantages of neural network learning mechanism but also contains the fuzzy reasoning system of expertise, compared with other fuzzy neural system it has the characteristics of convenient and efficient. Through a given input and output data sets, ANFIS constructs a fuzzy inference system. On this basis, using a separate back propagation algorithm or combined with least square method to complete the system to adjust the membership function parameters, which makes the fuzzy system learn from its modeling data information. Samples of ANFIS, which selects the same types of lead-acid battery and uses the check the discharge method measurement, establishing standard of vibration testing waveform characteristic values (such as size S , cycle T) and performance indicators (such as degradation degree, charged state) input/output relationship.

2.3. Loop simulation analysis

Because the primary loop analytic is complicated, the simulation analysis method is adopted.

When detecting in the primary loop, $R_1 = 1\text{ k}\Omega$, $E_2 = 12\text{ V}$, $R_2 = 100\text{ }\Omega$, $L = 1\text{ mH}$, lead-acid battery voltage damping oscillation simulation waveform is shown in Fig. 4. The main characteristic

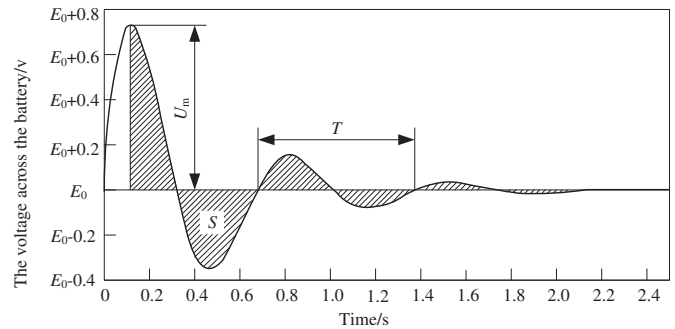


Fig. 4. Lead-acid battery voltage damping oscillation simulation waveform.

parameters are oscillation period T , zeta attenuation coefficient ζ , maximum amplitude U_m and waveform area S and so on.

The simulation result shows that the parameters are full and accurate to characterize the equivalent model of lead-acid battery properties, and it provides a theoretical basis of vibration test for the high accuracy of the lead-acid battery.

3. The experimental results and analysis

Lead-acid battery has two main performance indexes: degradation (the State of Health, SOH) and charged State (State of Charge, SOC). SOH refers to the actual full charge condition by experimental measurement of the ratio between capacity and nominal capacity. New lead-acid battery SOH value is 1 (generally greater than 1), while scrapped lead-acid batteries SOH value is 0; SOC is referred to which under the condition that a lead acid storage battery used or put on hold after a period of time and does not carry on the charging of the residual capacity and the ratio of the capacity of the fully charged state, usually by percentage, according to its value of 100% said the lead-acid battery is fully charged.

3.1. Experimental instruments and equipment

One type of C2S7173 check discharge detector, 1 type of BT – 6100 conductance detector, 1 type of sample vibration test, some numbers of BT – HSE – 120 – 12 lead-acid battery, some type of CDY889 lead-acid battery charger.

3.2. Experimental method

Firstly we should divide the lead-acid battery into sample groups and test groups and pay attention to the selection of lead-acid battery sample representativeness. Then we try to make the production time and service time and the charged state uniform distribution and wide coverage, such as establishing expert database. Based on vibration test with lead-acid batteries for testing measurement, we measure SOC and SOH, while we detect the same object and the content with a conductance method. Finally, we use check and discharge method to detect and as a standard for comparative analysis.

3.3. Results and analysis

(1) The relationship between vibration response and SOC.

Firstly, we randomly sample a set of lead-acid battery with 100% SOC, then with the vibration method to measure their average cycle vibration response T , and measure their average SOC by vibration method, then put T and SOC as the basis, through the constant

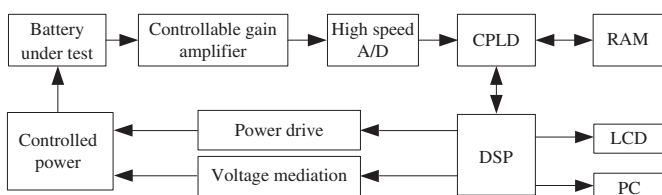


Fig. 3. Structure of the test system.

current discharge test to establish the theoretical between T and SOC, as shown in Fig. 5 then through the sample vibration method to test the battery of SOC, measured response exciting period T , from the theory of the relationship between T and SOC, by mapping we can obtain the vale of SOC. Fig. 5 only shows the mapping between 8 h and 13 h in two test points, and other test points can be analogy.

(2) No-load performance testing.

When no-loading, for different lead-acid battery SOC and SOH test, test results as shown in Table 1 and Table 2. From Table 1 can be seen, when measuring SOH, the mean absolute error of the test conductance method is 5.36%. SOH is larger as the degradation degree is low, while the measurement error is bigger, and the maximum error of the test is 11.54%. Absolute test error vibration method was 2.38%. In the lead-acid battery life cycle, it has no obvious measuring defects, and the maximum error is 3.76%. From Table 2, when measured SOC, mean absolute conductance method test error was 4.65% and the mean absolute test error vibration method was 2.43%. All in all, vibration method is more adaptable and higher precision than conductance method.

(3) Online performance test

Suppose a battery rated output current is 700 mA, allow the overload current is 1.22 A, light load current is 50 mA, then compensation is based on the load line detection that is shown in Fig. 6. Then we set 6 discrete test point, the battery output current is set to 1.05 A, the i_{RL} and i_{RLC} in Fig. 6 (a) were measured current load and the compensation current, i_R in Fig. 6 (b) is the actual output current of the battery. The results shows that, in addition to the test point 2, through the compensation, the other five test points which load current is maintained 1.05 A; As part of the load current of test point 2 exceeds the area 1.02 A, this part of the compensation current is 0. Output current of the battery completely depends on the load current and can not maintain constantly. Also to be noted is that in overload alarm area, the battery performance test will be closed automatically.

The same lead-acid battery tested SOH under different load conditions, as shown in Fig. 7, in which “*”, “○” and “△” respectively represent three typical lead-acid battery test results. Visibly, in the light load area and normal area, the SOH value has nothing to do with load almost, it refers that the system apply the compensation method have achieved the ideal effect. But in the normal overload area, because it could not compensate, measurement error is larger, and the measured value is greater than the actual value significantly.

It is also necessary to point out that, during the test, we introduced the load resistance compensation, so for lead-acid batteries,

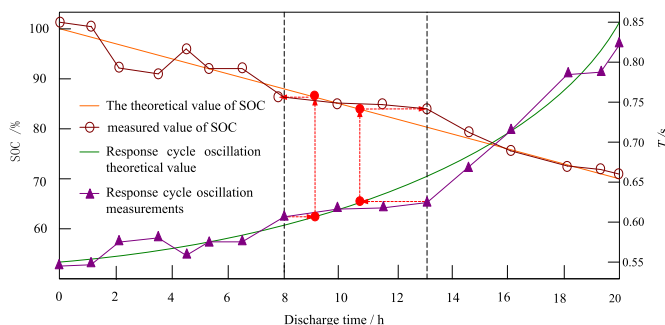


Fig. 5. The vibration response relationship between the cycle of T and SOC.

Table 1
Lead-acid battery SOH test.

NO.	Check and discharge method SOH	Conductance method		Vibration method	
		SOH	Error/%	SOH	Error/%
1	1.090	1.005	-7.80	1.131	3.76
2	0.866	0.892	3.00	0.870	0.46
3	1.005	1.121	11.54	1.032	2.69
4	0.665	0.690	3.76	0.652	-1.95
5	0.436	0.431	-1.15	0.448	2.75
6	0.265	0.278	4.91	0.272	2.64

Table 2
Lead-acid battery SOC test.

No.	Check and discharge method SOC	Conductance method		Vibration method	
		SOC	Error/%	SOC	Error/%
1	0.990	0.935	-5.56	0.941	-4.95
2	0.804	0.852	5.97	0.819	1.87
3	0.905	0.960	6.08	0.922	1.89
4	0.765	0.781	2.09	0.752	-1.70
5	0.336	0.318	-5.36	0.328	-2.38
6	0.562	0.578	2.85	0.572	1.78

it is equivalent to add a constant load, the lead-acid battery output characteristic improved, and the system can make the work load more stable.

To sum up, due to the fact that the conductance method is simply a method using the lead-acid battery internal resistance and the corresponding relationship between SOC and SOH to predict

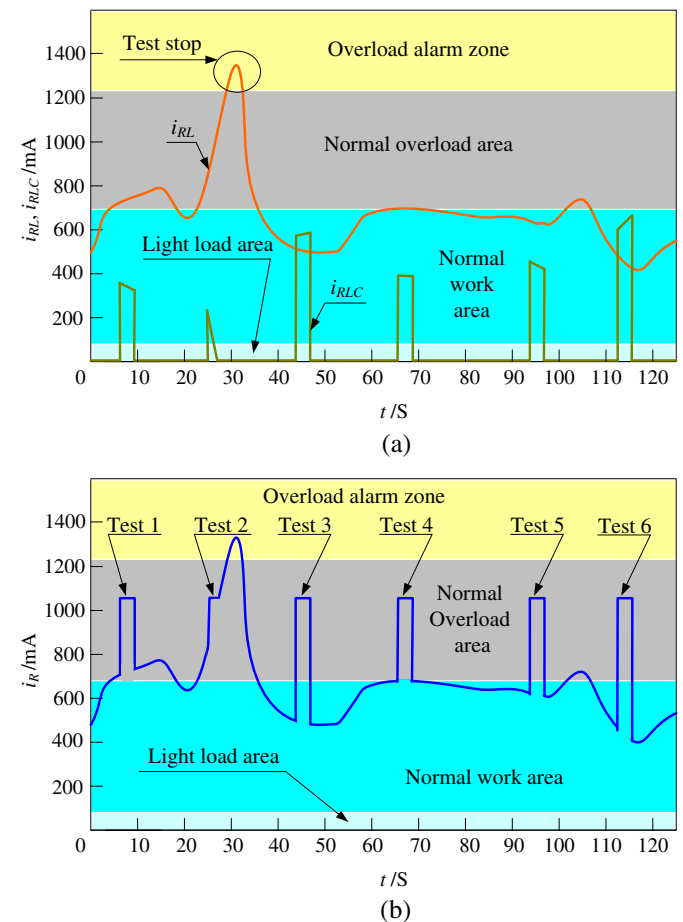


Fig. 6. Online testing based on load compensation.

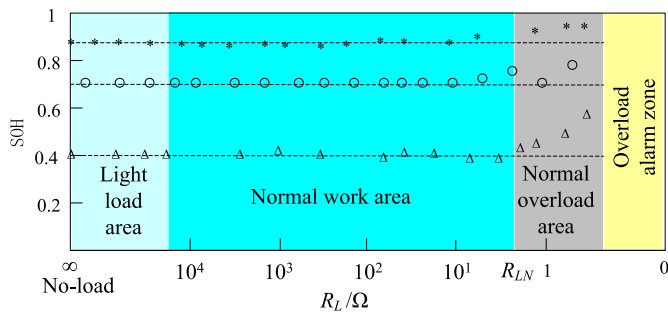


Fig. 7. SOH test online.

the extent of degradation and charged in the battery, it has low accuracy. While the vibration test is comprehensive considering the electrochemical characteristics of lead acid battery, which not only made up the defect of the conductivity test that can't found the shortage of the lead-acid battery degradation degree is insufficient, but also greatly increased the detecting precision.

4. Conclusion

Lead-acid battery vibration detecting system is based on vibration measured battery dynamic tracing of electrochemical process, and by means of real-time acquisition for state parameter to calculate, analyze and judge. It high-precisely quantizes and defines the measured battery's SOC and SOH performance indicators, fully self-adapts to determine the goal and ideal parameters, and lowers the loss of online monitor. The advantage of the method is: during

the testing process for lead-acid battery, instead of high current charging and discharging the battery, we only plus a smaller and shorter time of impulse voltage signal on both ends of lead-acid battery, and let it free oscillation, so it can directly reflect the battery cells to be measured without damage; what's more, energy consumption of system is small, load characteristic is improved at the same time and realize the online detection. Due to vibration detection is implemented based on ANFIS, in terms of the choice of input, the model take various factors into account about the influence on the output value, so it can realize a variety of lead-acid storage battery voltage adaptive and high-precision test.

References

- [1] N. Achaibou, M. Haddadi, A. Malek, J. Power Sources (2008) 1484–1491.
- [2] Donald W. Corson, J. Power Sources (2002) 110–113.
- [3] Pritpal Singh, Ramana Vinjamuri, Xiquan Wang, et al., J. Power Sources (2006) 829–836.
- [4] Alvin J. Salkind, Craig Fennie, Pritp Sighn, et al., J. Power Sources (1999) 293–300.
- [5] Vahid Esfahanian, Farschad Torabi, Ali Mosahebi, J. Power Sources (2008) 373–380.
- [6] C. Ponce de Leon, A. Frias-Ferrer, J. Gonzalez-Garcia, F.C. Walsh, D. Szanto, IEEE Trans. Wireless Commun (2002) 660–667.
- [7] Carlo Andrea Bollino, Energy J (2009) 81.
- [8] Ronald J. Sutherland, Energy J (1991) 15–34.
- [9] G. Boyd, J.F. McDonald, M. Ross, D.A. Hansont, Energy J (1987) 77–96.
- [10] Kenneth B. Medlock III, Ronald Soligo, Energy J (2001) 77–105.
- [11] Carolyn Fischer, Energy J (2010) 101–120.
- [12] B.T. Liu, K.H. Chien, C.C. Wang, Energy (2004) 1207–1217.
- [13] D. Wei, X. Lu, Z. Lu, J. Gu, Energy Convers. Manage (2007) 1113–1119.
- [14] D.Y. Goswami, F. Xu, J. Sol, Energy Eng (1999) 9197.
- [15] X. Shi, D. Che, Int. J. Energy Res. (2007) 975–998.